Refereed Proceedings

The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering

Engineering Conferences International *Year* 2007

A DEM Study of Geldart Group A Particle Bed Fluidisation Behavior Across the Regimes

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A DEM STUDY OF GELDART GROUP A PARTICLE BED FLUIDISATION BEHAVIOR ACROSS THE REGIMES

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ABSTRACT

The objective of this study is to identify the transitions in fluidized bed behavior as the gas velocity is increased to cover the complete range from minimum fluidization through bubbling and turbulent behavior to pneumatic transport, corresponding to 4 orders of magnitude in gas velocity. Particle physical properties are fully incorporated, enabling surface forces to be modeled. The simulation data are examined in terms of computer visualizations, showing for the first time the evolution of bed structure with changes in gas velocity. The simulated behavior reproduces experimental observations, particularly with respect to the maximum in amplitude of pressure drop fluctuations associated with the transition to turbulence.

INTRODUCTION

A Lagrangian-Eulerian fluidized bed model employing the Discrete Element Method for the particulate phase (1), has been used to study the fluidized behavior of a Geldart Group A particle bed. The model is essentially the same as that used by Tsuji's group (2) except that the drag force is calculated using the Di Felice (3) correlation since this provides a smooth continuous variation in drag force with porosity and has been found to give the most satisfactory agreement with reality of any of the alternative formulations.

A wide range of fluidizing gas velocities has been used in order to identify the various behavioral regimes from minimum fluidization through bubbling and turbulent behavior to pneumatic transport. The work reported here is part of an ongoing project in which simulations are carried out for particles without and with surface energy based on the JKR model of adhesion (4). However, in this paper, the particles are modeled as non-adhesive, frictional elastic spheres for which the contact interaction algorithms are based on theoretical contact mechanics as detailed by Thornton and Yin (5). The results presented provide a benchmark against which the results of corresponding simulations with surface energy can be compared.

SIMULATION DETAILS

A polydisperse system of 5000 spheres (five sizes: 45 μm, 47.5 μm, 50 μm, 52.5 μm and 55 μm, normal distribution) with a mean diameter d_p = 50 μm was used for the simulations; the small dimensions of the study were chosen so as to focus on the fundamental behavior of the system in the presence of fully modeled interparticle forces. The properties of the particles were: Young's modulus = 700 MPa, Poisson's ratio = 0.33, friction coefficient = 0.3 and density =2500 kg/m^3. Air at a temperature of 293K and standard atmospheric pressure was used as the fluidizing gas. For the gas, the compressible Navier-Stokes equations are solved on an equidistant but staggered Cartesian grid using a numerical scheme that is an adapted version of Patanker's SIMPLE methodology (6). In the numerical discretisation, a grid dimension of 125 μm was used for the continuum fluid.

All the particles were initially randomly generated as a granular gas (no contacts) within a 2 mm wide container. All particle centers were located in the same plane and subsequent out-of-plane motion was suppressed. A vertical gravity field was introduced in order to create a pluvially deposited bed of particles. The initial bed height was approximately 6 mm and the initial voidage was 0.458. In calculating the voidage the dimension in the third orthogonal direction was taken to be the average particle diameter (0.05 mm).

Pressure drop–bed voidage-superficial gas velocity characteristics were obtained by introducing uniform gas flow U = 0.0003 m/s into the bed from the bottom row of computational fluid cells. The pressure drop Δp across the bed was obtained as the time-averaged difference between the average pressure in the bottom and top row of fluid computational cells. This was repeated for a range of gas velocities incremented in relatively small steps up to 1.2 m/s.

For each gas velocity, the bed height was determined in the following manner. The fluidised bed is divided into eight vertical columns. For each column, the topmost particle is identified and the highest computational fluid cell in which the topmost particle resides is recorded at the same time. The average height for each column is computed by accumulating all of the heights of particles in each of the highest computational fluid cells and then calculating the overall average. Finally, with the mass of the particles in each highest cell as the weighting parameter, the whole bed height is then calculated by taking the average of all the column heights.

RESULTS AND DISCUSSION

Figure 1 shows the bed expansion in terms of the average bed void fraction over the complete range of superficial gas velocities. Since Fig. 1 is a double-logarithmic plot there is an indication of power law behavior with sudden changes in the exponent that suggest possible transitions between the different fluidization regimes, as indicated in the figure.

In the fixed bed regime the average bed voidage is constant as indicated in Fig. 1. Figure 2 shows that, as the gas velocity is increased, the pressure drop increases until it becomes equal to the bed weight divided by the cross-sectional area of the bed. After this point the average pressure drop remains constant. Traditionally, the point when the average pressure drop first becomes equal to the bed weight divided by the cross-sectional area of the bed is defined as 'minimum fluidisation' and the gas velocity at which this occurs is denoted by U_{mf}. This corresponds to a transition to what is conventionally referred to as 'homogeneous fluidisation' during which the bed expands,

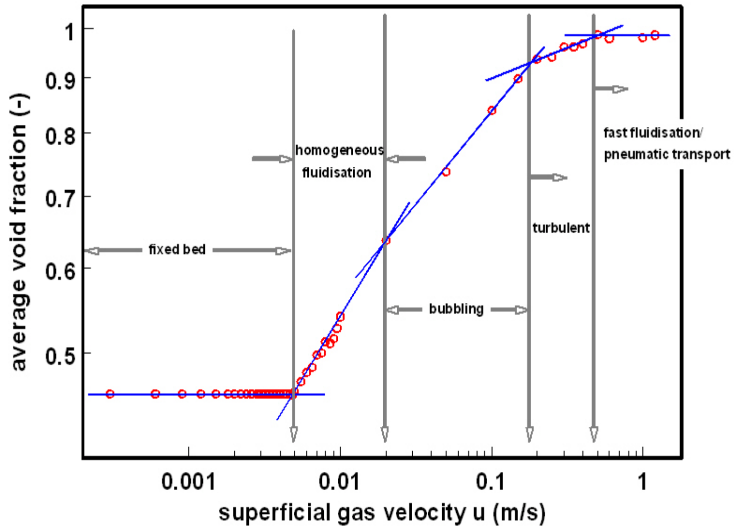

Fig.1 Variation of the average bed void fraction with increasing superficial gas velocity

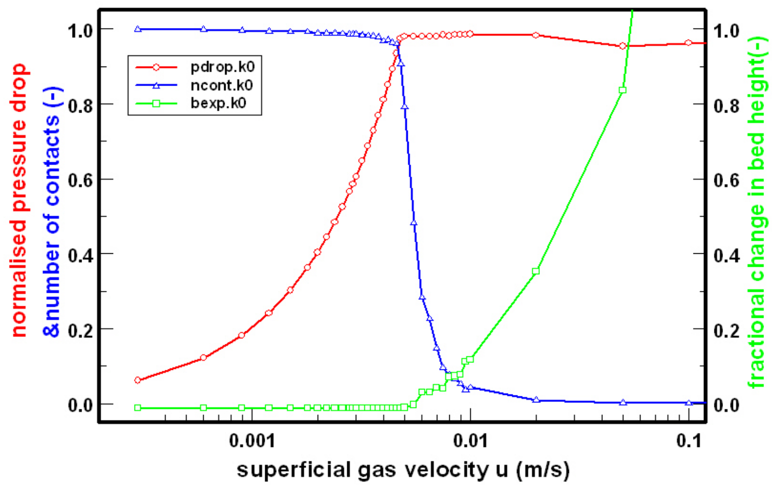

Fig.2 Normalized pressure drop, normalized number of interparticle contacts and fractional change in bed height

As can be seen in Fig. 1. Figures 1 and 2 indicate that U_{mf} = 0.005 m/s which is in reasonable agreement with the value of 0.0041 m/s predicted by the Ergun correlation (7), using the intial bed voidage (0.458) as mentioned earlier.

In Fig. 2 we also plot, for each gas velocity, the average number of interparticle contacts normalized by the initial number of contacts. It can be seen that, at U_{mf}, only 10% of contacts have been lost. As the gas velocity is further increased, the number of contacts decreases strongly (70% of contacts have been broken at U = 0.006 m/s) but then tends towards an asymptotic value of the order of 5% of the original number of contacts at U ~ 0.01 m/s. This trend was also reported for 2D DEM simulations by Kafui *et al*. (1). The figure suggests that, during ‘homogeneous’ fluidization, there is a

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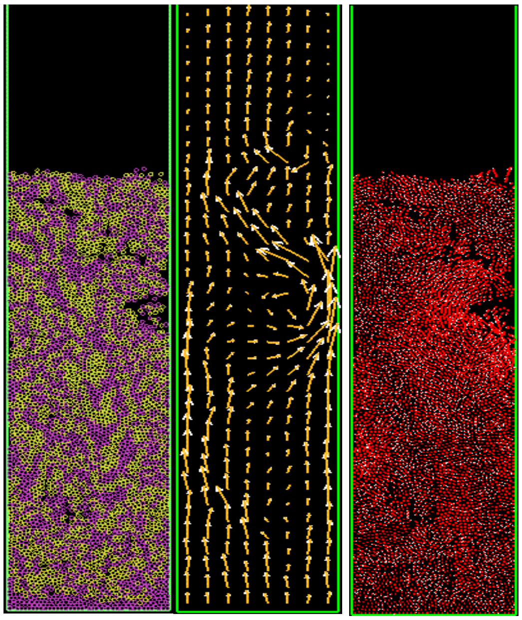
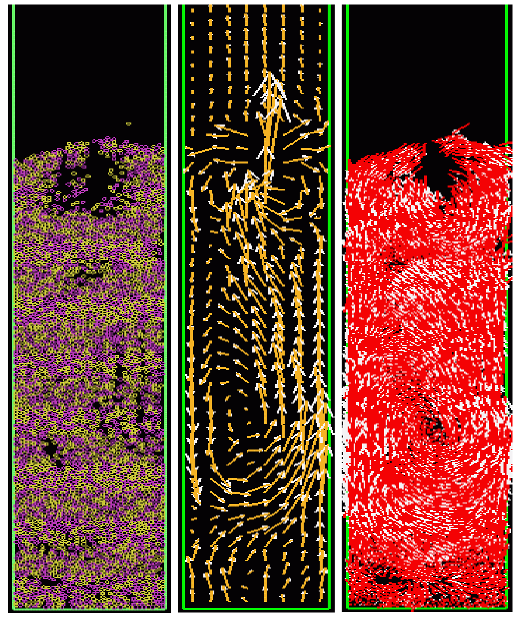
range of gas velocities over which the bed evolves from “incipient fluidization” (pressure drop equals weight per unit area) to a “fully-fluidized” state (particles moving independently), which is the precursor for ‘bubbling’ to occur.



particles fluid velocities particle velocities

Fig. 3 Homogeneous expansion (U = 0.008 m/s)



particles fluid velocities particle velocities

Fig. 4 Bubbling fluidization (U = 0.02 m/s)

Figure 1 suggests that the transition from the ‘homogeneous fluidisation’ regime to the bubbling regime might occur at U = 0.02 m/s, corresponding to $U_{mb} = 4U_{mf}$. Figure 3 shows snapshots of the particle configuration (left) the gas velocity field (centre) and the particle velocity field (right) when the superficial gas velocity was 0.008 m/s. It can be seen that there is a ‘large’ void towards the top of the bed, adjacent to the right-hand wall. However, it has been noted (8) that some occasional bubbles can appear in the ‘homogeneous’ fluidized regime when the gas velocity is only slightly above U_{mf}. Indeed, the explanation for the ‘homogeneous’ fluidized regime provided by Massimilla *et al.* (9) is based on the observation of ‘cavities’ adjacent to the wall. When is an enlarged void/cavity a ‘bubble’ and when is it not? Although Fig. 1 suggests that U_{mb} = 0.02 m/s, it can be seen from Fig. 4 that the bed is in fact in the bubbling regime at that gas velocity. From examination of video sequences of the simulations, the authors conclude that U_{mb} = 0.01 m/s ($2U_{mf}$) but this method is qualitative and subjective. Further work is required to find a quantitative measure that can characterize this transition.

From Fig. 1, the breaks in the slopes suggest that the transition from bubbling to turbulent flow, U_c, and the transition from turbulent to fast fluidization, U_k, occur at U_c ~ 0.2 m/s (40 U_{mf}) and U_k ~ 0.5 m/s (100 U_{mf}) respectively.

It has been suggested (10) that U_c indicates a change from closed laminar bubble wakes to open turbulent wakes and that U_k corresponds to the point when a distinct upper bed surface disappears due to substantial entrainment (11). However, once more, visual observations are subjective. The first quantitative criterion to identify the transition from bubbling to turbulent fluidization was proposed by Yerushalmi *et al.* (12) with further studies reported by Yerushalmi and Cankurt (13). These authors suggested that U_c corresponds to the gas velocity at which the standard deviation of the pressure fluctuations reaches a maximum value and this definition appears to be generally accepted in the literature. The same authors also suggested that U_k corresponds to the gas velocity at which the standard deviation of the pressure fluctuations levels off.

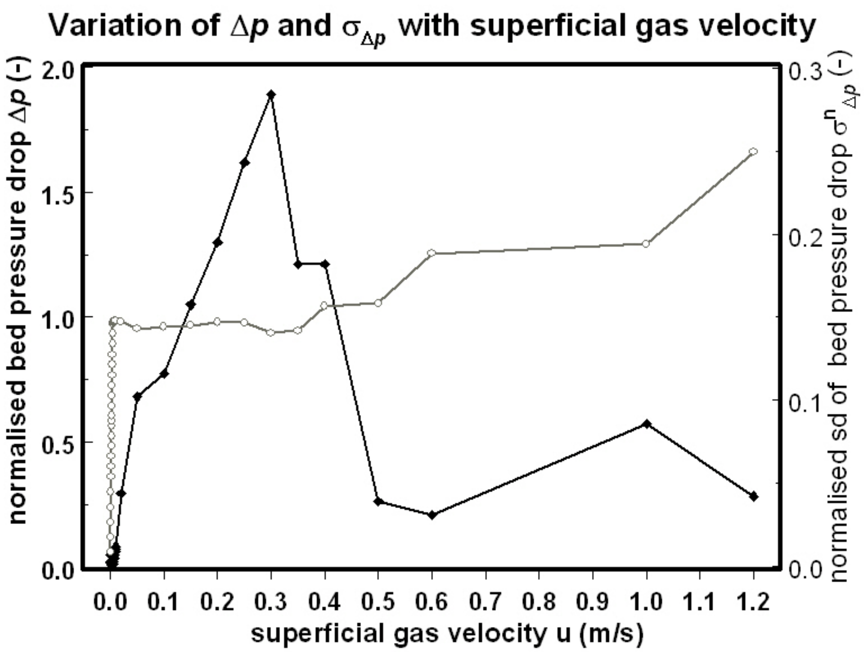


Fig. 5 Variation of normalized pressure drop and normalized standard deviation of the pressure drop fluctuations with superficial gas velocity

Figure 5 shows the standard deviation of the pressure drop fluctuations, normalized by the average pressure drop, plotted against the superficial gas velocity. It can be seen that, according to the criteria suggested in (12) and (13), the transition from bubbling to turbulent flow occurs when $U = U_c = 0.3$ m/s (60 U_{mf}) and the transition to fast fluidization occurs when $U = U_k = 0.5$ m/s (100 U_{mf}). That the value of U_k inferred from Fig. 1 is the same as that obtained from the pressure fluctuation data may be fortuitous. The corresponding values of U_c are different and the value obtained from Fig. 5 is considered to be more reliable. Superimposed on Fig. 5 is the normalized average pressure drop obtained for the different gas velocities. It is noted that when the standard deviation of the pressure drop fluctuations reaches a maximum value this also coincides with the beginning of a continuous increase in the average pressure drop across the bed, due to the particle acceleration and wall frictional components associated with pneumatic transport. Note that in the simulation all particles remain within the bed and the frame of reference expands to contain them; in practice, particles would be entrained, leading to a decrease in inventory and therefore pressure drop. Typical snapshots of the particle configuration, fluid velocities and particle velocities are illustrated in Fig. 5 for U = 0.3 m/s and in Fig. 6 for U = 0.5

m/s.

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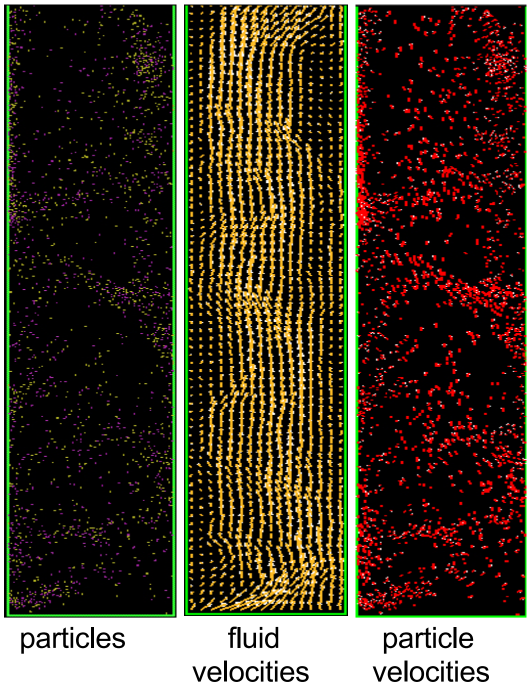

Fig. 6 Turbulent fluidization (U = 0.3 m/s)

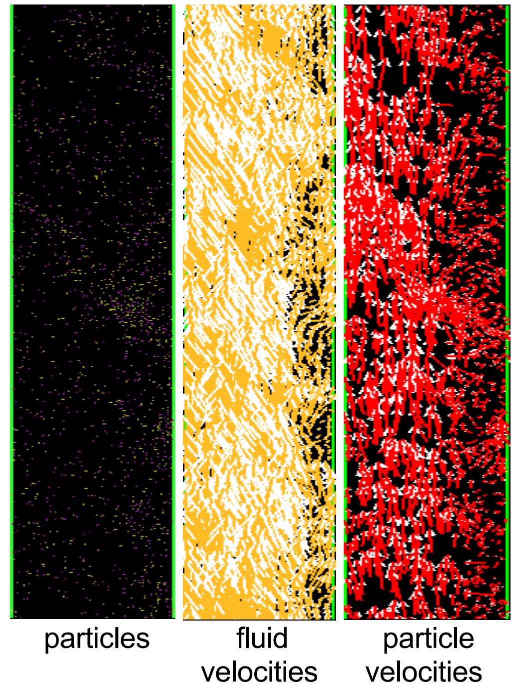

Fig. 7 Fast fluidization (U = 0.5 m/s)

CONCLUDING REMARKS

A Lagrangian-Eulerian fluidized bed model has been used to study the fluidized behavior of a cohesionless Geldart Group A particle bed for a wide range of superficial gas velocities in order to identify the various behavioral regimes from minimum fluidization through bubbling and turbulent behavior to fast fluidization. From the results of the simulations the following conclusions are drawn:

- For the particle size distribution and initial bed voidage used, the point of minimum fluidization is unambiguous and U_{mf} = 0.005 m/s, which is in reasonable agreement with the prediction of the empirical correlation due to Ergun (7).
- In spite of the subjective nature of visual observations, including video sequencing, the authors conclude that U_{mb} = 0.01 m/s which corresponds to $U_{mb} = 2\ U_{mf}$; but there is a need to find a more reliable quantitative measure of this transition than that offered by Fig. 1.
- In agreement with conventional wisdom, it is considered that the transition to turbulent flow occurs when the standard deviation of the pressure drop fluctuations reaches a maximum value and therefore, for the simulations reported, U_c = 0.3 m/s = 60 U_{mf}. It is also observed from the simulations that this coincides with the beginning of a continuous increase in the average pressure drop across the bed.
- The simulations also support the generally agreed criterion that the transition to fast fluidization occurs when the standard deviation of the pressure fluctuations levels off. Consequently, it is concluded that, from the results

obtained for the system studied here the value of U_k = 0.5 m/s = 100 U_{mf}.

In the paper it was initially suggested that the trends shown in Fig. 1 might indicate possible transitions between the different fluidization regimes. However, as evidenced by the examination of other aspects of the simulated data it is concluded that this is not a reliable way of identifying the transition points. Nevertheless, it is considered that Fig. 1 can be useful for examining the effects of particle properties on the relationship between superficial gas velocity and voidage, and hence to ensure that one is in the desired fluidization regime.

The work reported above is part of an ongoing project (14) in which other parameters, e.g. the granular temperature, will be examined to complement the data presented in this paper. In the context of the transition from fixed bed to bubbling bed, more information is now available including the effect of surface energy. Due to space restrictions this cannot be reported here but will be the subject of a forthcoming paper.

ACKNOWLEDGMENT

The above work is part of a project supported by the Engineering and Physical Sciences Research Council (Grant No. GR/T17076/01).

NOTATIONS

U	superficial gas velocity	m/s
U_{mf}	superficial gas velocity at minimum fluidization	m/s
U_{mb}	superficial gas velocity at minimum bubbling	m/s
U_c	superficial gas velocity at the transition from bubbling to turbulent flow	m/s
U_k	superficial gas velocity at the onset of fast fluidization	m/s
d_p	average particle diameter	m
Δp	average pressure drop across the bed	kPa

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